Elements of Flight Test Engineering

Flight Test Manual

Flight Testing Objectives

In general, the flight tests are designed to:

1. Provide an appreciation of the value of experimental techniques by:
    a. Comparing experimental results with those predicted by analysis.
    b. Extending aerodynamic investigation beyond the capability of theory due to mathematical or geometrical complexities.
    c. Arriving at empirical relations applicable to other situations.
    d. Combining theoretical and experimental results to predict aircraft operation in various environments.
2. Teach techniques of performance flight testing.
3. Develop the basic concepts behind methods for acquiring generalized performance data with minimum expenditure of pilot and aircraft time.
4. Illustrate the limitations of flight testing caused by
    a. Unusual weather conditions.
    b. Mechanical malfunctions of the instrumentation.
    c. The flying qualities of a particular aircraft.
    d. Limited equipment capabilities.
    e. Experimental accuracy.
    f. Occasional results difficult to characterize or justify.

Special Instructions

The following procedures are applicable to all flight-testing experiments:

1. Safety Precautions
    a. Smoking is prohibited in or near the aircraft.
    b. Seat belts shall be worn at all times.
    c. Flight personnel shall be seated in the aircraft prior to engine start and remain seated until the engine is stopped.
    d. Remain clear of the propeller area at all times.
    e. Do not stand, walk, sit or lean on the aircraft except in designated areas.
    f. Do not open aircraft windows or doors in flight.
    g. Advise the pilot immediately upon observing another aircraft, using clock position followed by high, low or level.
    h. Do not manipulate the aircraft flight or engine controls.
    i. Advise the pilot of impending airsickness. Use the bag provided, your hat, your shoe, anything except the aircraft deck. **You mess it up, you clean it up.**
2. Crew Duties

    Midshipmen are assigned to three man teams for the purpose of making flight recordings. Flight crew duties are rotated each flight. The instructor is pilot in command of the aircraft and occupies the left front seat at all times. Because the pilot is primarily concerned with flying the aircraft, the midshipman in the right rear seat acts as lookout and notifies the pilot immediately of any aircraft sighted. The midshipman in the right front seat acts as data observer and timekeeper, and the midshipman in the left rear seat acts as data recorder.

3. Scheduling and Transportation

   Sections in this course are normally composed of 12 midshipmen. Six midshipmen fly on alternate laboratory days. Flights are of 1–1.5 hour duration. Those midshipmen not scheduled to fly proceed to the assigned classroom at the scheduled time. Those midshipmen composing the two three-person flight teams will depart via scheduled transportation for Bay Bridge Airport from the rear entrance of Rickover Hall at the laboratory class convening time, or use their own transportation to Bay Bridge Airport. The Commandant has given permission for this. The instructor will be at the aircraft, having completed pre-flight and fueling by the time the midshipmen arrive. All midshipmen will return to the Naval Academy upon completion of their respective flights, in time for their next scheduled activity.

4. Pre-flight and Post-flight Data.

   Most flights in this course require knowing the average sea level barometric pressure and air temperature for the period of the flight. Hence prior to, and after, each flight, students are to obtain this information. Information sources, in decreasing order of accuracy, include a barometer located in the FBO building at the airport, barometers and thermometers in the Division buildings, aircraft radio or telephone (1-800-WXBRIEF) to Flight Service Stations.

   Additionally, aircraft gross weight is required for most flights and individual data runs. Students can compute this data using:

$$\begin{aligned} W_0 = &\text{ aircraft empty weight + oil weight + fuel weight} \\ &+ \text{passenger weight} \end{aligned}$$

$$\begin{aligned} \text{aircraft empty weight} &= \text{2378.6 lbs, including full oil and six gallons} \\ &\quad\ \text{of unusable fuel.} \\ \text{oil weight} &= \text{1.92 lbs/quart (12 quarts = 23 lbs)} \\ \text{fuel weight} &= \text{6 lbs/gallon (80 gallons = 480 lbs, 74 gallons} \\ &\quad\ \text{usable = 444 lbs.)} \end{aligned}$$

   where W_0 is the preflight or original weight. The aircraft weight at any time is computed by

$$W = W_0 - 6(\mathrm{FF})(\Delta T)$$

   where FF is the fuel flow rate in gallons/hr and ΔT is the elapsed time in hours.

Fuel usage can be obtained using the fuel flow computer in the aircraft or the test run tachometer reading minus the original tachometer reading and the fuel flow rate.

Fuel flow rate can be approximated by engine cruise power settings. Maximum BHP for the Continental IO 550B engine is 300 HP at sea level. Representative fuel flow values at best power mixture are:

$$75\% \text{ power } (225 \text{ HP}) = 16.3 \text{ gal/hr } (98 \text{ pph})$$
$$65\% \text{ power } (195 \text{ HP}) = 14.0 \text{ gal/hr } (84 \text{ pph})$$
$$55\% \text{ power } (165 \text{ HP}) = 12.0 \text{ gal/hr } (72 \text{ pph})$$
$$45\% \text{ power } (135 \text{ HP}) = 10.2 \text{ gal/hr } (61 \text{ pph})$$

The Atmosphere

Introduction

The performance of an aircraft can be predicted with reasonable accuracy by deduction from the physical laws governing its actions. However, so many variables enter into an aircraft's performance that error is present in any analytical prediction. Thus, actually flying the aircraft and measuring the performance, i.e., flight testing, is necessary.

Apart from the physical characteristics of the aircraft, performance depends on the properties of the atmosphere. Because the properties of the atmosphere are variable, additional complexities enter into the aircraft performance problem. Hence, it is necessary to thoroughly understand the nature of the atmosphere.

Properties of the Atmosphere

The atmosphere is often referred to as a sea of air surrounding the earth. Because air is a compressible fluid, the atmosphere is compressed by its own weight. Thus, the greatest density occurs at the bottom of this sea of air, or at the earth's surface, and becomes less dense with increasing height above the surface. At any given point and altitude the density also varies from day to day because of the movement across the earth of air masses of varying temperature and pressure. However, measurements over a period of time yield average values of density, temperature and pressure at sea level and average rates of change with altitude. These values are referred to as standard atmospheric conditions, or simply the standard atmosphere. Standard sea level conditions accepted internationally are:

$$\text{Pressure } 1.01325 \times 10^5 \text{N/m}^2 = 2116.2 \text{ lb/ft}^2 = 29.921 \text{ in Hg}$$
$$\text{Temperature } 288.16°\text{K} = 518.69°\text{R} = 15°\text{C} = 59°\text{F}$$
$$\text{Density } 1.2250 \text{ kg/m}^3 = 0.002377 \text{ slugs/ft}^3$$

The standard atmosphere at altitude is determined by making several assumptions:

1. The atmosphere is a perfect gas and thus obeys the perfect gas law, $p = \rho \mathrm{R} T$.
2. The temperature decreases linearly with altitude from sea level to 11Km $=$ $36,089$ ft, the upper limit of the troposphere.
3. The temperature throughout the stratosphere, which begins at 11Km $= 36,089$ ft, is constant, with a value of 216.66°K, or -69.8°F.

The standard lapse rate, or standard rate of decrease in temperature with altitude throughout the troposphere, is taken as 2°C or 3.57°F per thousand feet. All the standard properties of the atmosphere at altitude are based on this lapse rate from the standard sea level value.

Using English units in terms of absolute temperature, the standard temperature at altitude is approximately

$$T = 519 - 0.00357h$$

where h is altitude in feet and T is the temperature in degrees Rankine. It is convenient to refer temperature to the standard sea level temperature. Hence, we define a temperature ratio, θ, as

$$\theta = \frac{T}{T_{\mathrm{SL}}} = \frac{519 - .00357h}{519} = 1 - 0.689 \times 10^{-5} h \tag{1-1}$$

Ratios for pressure and density are defined by

$$\text{Pressure ratio} = \delta = \frac{P}{P_{\mathrm{SL}}} \tag{1-2}$$

$$\text{Density ratio} = \sigma = \frac{\rho}{\rho_{\mathrm{SL}}} \tag{1-3}$$

Referring to Figure (1–1), we can derive an expression for the pressure ratio in terms of altitude. Summing the vertical forces acting on the differential volume of air yields

$$(p + dp)A + g\rho A dh - pA = 0 \tag{1-4}$$

where $A =$ area of the differential volume

$dh =$ height of the differential volume

$p =$ pressure at the bottom of the differential volume

$dp =$ change in pressure between bottom and top of the differential volume

Hence $dp = -g\rho dh$ (1 − 5)

Using the perfect gas equation, $p = \rho \mathrm{R} T$, yields

$$dp = -\frac{g}{\mathrm{R}T} dh \tag{1-6}$$

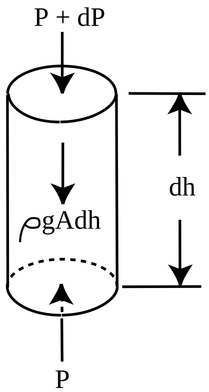

Figure 1–1 Forces on an elemental column of air.

Substituting for T from Eq. (1-1) gives

$$\frac{dp}{p} = \frac{g}{\mathrm{R}(519 - 0.00357h)} dh \tag{1-7}$$

Integrating between sea level and any altitude, h, yields

$$\frac{p}{p_{\mathrm{SL}}} = \left[\frac{519 - 0.00357h}{519}\right]^{\dfrac{g}{R(0.00357)}} \tag{1-8}$$

Using $g = 32.2$ ft/sec^2 and $R = 1718$ ft^2/sec^2 °R

$$\frac{p}{p_{\mathrm{SL}}} = \left[\frac{519 - 0.00357h}{519}\right]^{5.256} \tag{1-9}$$

The quantity inside the brackets is $^T/_{T_{\mathrm{SL}}}$, or θ. Substituting yields

$$\delta = \frac{p}{p_{\mathrm{SL}}} = \left(\frac{T}{T_{\mathrm{SL}}}\right)^{5.256} = \theta^{5.256} \tag{1-10}$$

Again using the perfect gas law, the density ratio is

$$\sigma = \frac{\rho}{\rho_{\mathrm{SL}}} = \frac{p}{\mathrm{R}T}\frac{\mathrm{R}T_{\mathrm{SL}}}{\rho_{\mathrm{SL}}} = \frac{p}{p_{\mathrm{SL}}}\frac{T_{\mathrm{SL}}}{T} = \frac{\delta}{\theta}$$

Standard atmospheric properties at various altitudes are given in Table 1–1. Because the atmosphere is rarely exactly at these standard conditions, flight testing must be done in the existing atmosphere. Performance characteristics, however, are corrected to standard conditions using the above ratios. Thus, all performance is related to a common set of conditions, or norm, which facilitates comparison of the performance of various aircraft. It also gives the pilot a datum point which allows correction to existing conditions in order to determine the exact performance for a particular flight.

Because all aerodynamic forces are a function of the dynamic pressure, which is directly proportional to density, density is one of the most important properties of

Table 1–1. Standard atmosphere table.

Standard Sea Level Conditions:	Conversion Factors:
Temperature 15°C, 59°F	1 in Hg = 70.727 lb/sq ft
Pressure 29.92 in Hg, 2116.216 lb/ft^2	1 in Hg = 0.49116 lb/sq in
Density 0.0023769 slugs/ft^3	1 knot = 1.151 mph
Speed of sound 1116.59 ft/sec, 661.7 knots	1 knot = 1.688 ft/sec

Altitude Feet	Density Ratio σ	$\frac{1}{\sigma}$	Temperature °C	Temperature °F	Speed of Sound Knots	Pressure in Hg	Pressure Ratio δ
0	1.0000	1.0000	15.000	59.000	661.7	29.921	1.0000
1000	0.9711	1.0148	13.019	55.434	659.5	28.856	0.9644
2000	0.9428	1.0299	11.038	51.868	657.2	27.821	0.9293
3000	0.9151	1.01454	9.056	48.302	654.9	26.817	0.8962
4000	O.8881	1.0611	7.076	44.735	652.6	25.842	O.8637
5000	0.8617	1.0773	5.094	41.169	650.3	24.896	0.8320
6000	0.8339	1.0938	3.113	37.603	648.7	23.978	0.8014
7000	0.8106	1.1107	1.132	34.037	645.6	23.088	0.7716
8000	0.7860	1.1279	−0.850	30.471	643.3	22.225	0.7428
9000	0.7620	1.1456	−2.831	26.905	640.9	21.388	0.7148
10,000	0.7385	1.1637	−4.812	23.338	638.6	20.577	0.6877
11,000	0.7155	1.1822	−16.793	19.772	636.2	19.791	0.6614
12,000	0.6932	1.2011	−18.774	16.206	633.9	19.029	0.6260
13,000	0.6713	1.2205	−110.756	12.640	631.5	18.292	0.6113
14,000	0.6500	1.2403	−112.737	9.074	629.0	17.577	0.5875
15,000	0.6292	1.2606	−114.718	5.508	626.6	16.886	0.5643
16,000	0.6090	1.2815	−116.699	1.941	624.2	16.216	0.5420
17,000	0.5692	1.3028	−118.680	−1.625	621.8	15.569	0.5203
18,000	0.5699	1.3246	−120.662	−5.191	619.4	14.942	0.4994
19,000	0.5511	1.3470	−122.643	−8.757	617.0	14.336	0.4791
20,000	0.5329	1.3700	−124.624	−12.323	614.6	13.750	0.4595

the atmosphere in flight testing. However, it is also the most difficult property to measure directly. On the other hand, it is relatively easy to measure the pressure and temperature of the air. The density is then calculated through the use of the perfect gas equation. Temperature is measured by a standard thermometer. Pressure is normally determined from the altimeter, which is really a pressure gauge calibrated in feet of altitude. This leads to some discussion of the term 'altitude.'

Altitude

Altitude is commonly thought of as the vertical position of an aircraft with respect to the earth's surface. However, because atmospheric properties vary with altitude, it can also be considered as the vertical location of a specific value of temperature, pressure or density. Thus, we define altitude in different ways. The accepted definitions are:

> *Pressure altitude* is the height in the atmosphere at which a given value of standard pressure exists.

Density altitude is the height in the atmosphere at which a given value of standard density exists.

True altitude (or tapeline altitude) is the actual height measured by a tapeline.

Indicated altitude is the height read on the altimeter. It can differ from actual values because of error in the system, because of improper setting or temperature effects.

All of these various altitudes are measured in feet from a common datum plane, called mean sea level (MSL). True altitude is of interest to the pilot for purposes of terrain clearance. Density or pressure altitude is of much more significance for performance determination. The true altitude which corresponds to a given density altitude may vary considerably from day to day. However, aircraft performance is always the same at the same density altitude. For example, referring to Figure 1–2, assume the aircraft is flying at a true altitude of 5000 feet above sea level, where the pressure is 23.98 in Hg and the temperature is 53°F. The pressure is 23.98 in Hg at 6000 ft in the standard atmosphere. Thus, the pressure altitude is 6000 ft. A temperature of 53°F, together with a pressure of 23.38 in Hg, yields a density of 0.001928 slugs/ft^3. This is the density found at 7000 ft. Thus, in the standard atmosphere the density altitude is 7000 ft. The performance of the aircraft at 5000 ft on this day is comparable to that of the same aircraft at 7000 ft on a standard day. A further definition of altitude, which is of no significance for flight testing but is of considerable importance to the pilot, is absolute altitude. This is the height above the terrain immediately below or above ground level (AGL). In the example above note that Figure 1–2 indicates that the absolute altitude is 3000 ft. The pilot can determine the absolute altitude by locating the height of the terrain on navigational charts and subtracting it from the true altitude. For example, knowing the terrain height is 2000 ft above sea level (MSL) and determining the true altitude from the altimeter to be 5000 ft shows that the absolute altitude is 3000 ft.

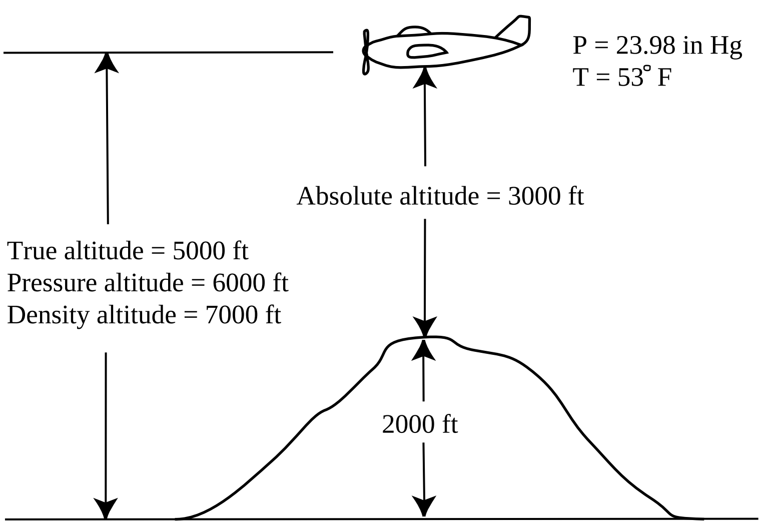

Figure 1–2 Altitude relationships.

The Altimeter

The altimeter is calibrated using the standard lapse rate; Eq. $1 - 10$ yields

$$p = p_{\mathrm{SL}}(1 - 0.689 \times 10^{-5}h)^{5.256}$$

or inverting the equation we have

$$h = -145378[(\frac{p}{p_{\mathrm{SL}}})^{0.19} - 1] = 1.45 \times 10^5[\delta^{0.19} - 1]$$

If the sea level pressure differs from standard sea level pressure, $p_{\mathrm{SL}} = 29.92$ in Hg, then an error exists in the indication of true altitude. To correct for this error, the altimeter is equipped with an adjustment to set the correct sea level pressure for the given day and location. Figure 1–3 shows a typical sensitive altimeter. Notice that in the window (Kohlsman window) between 2 and 3 on the large scale the pointer indicates 29.97 in Hg. This is the setting of the sea level barometric pressure. If the current sea level pressure is different from this value, the new value is entered by turning the adjusting knob. The hands indicating height also change accordingly. Proper barometric pressure is obtained from local weather bureaus, flight service stations or air traffic control (ATC). With the actual sea level pressure entered, the altimeter reads true altitude, providing there is no instrument, position or temperature error. With 29.92 in Hg entered in the Kohlsman window, the altimeter reads pressure altitude. This is what is needed in flight testing, because the altimeter is really used to determine the air pressure. The true altitude is of no significance. Thus, in flight testing the altimeter is always set at 29.92 in Hg. The altitude is read by the indication of the various hands on the large scale. The largest hand reads hundreds of feet, the intermediate hand reads thousands, and the very small hand (not shown) reads ten-thousands of feet. For example, the altimeter in Figure 1–3 reads 850 feet.

Flight Test Measurements

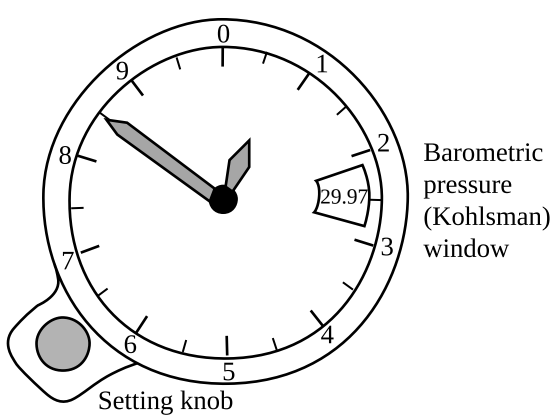

Figure 1–3 Altimeter.

In flight testing newly designed modern aircraft, some very sophisticated equipment is employed. Special highly sensitive instrumentation which feeds directly into automatic recording devices is installed in the aircraft. Sometimes the data is fed into airborne computers which reduce the new data immediately to meaningful performance parameters. Sometimes telemetering equipment is employed to transmit the raw or computed data to ground-based computers and recorders. Another standard method of measurement is a photopanel. This is a special panel of sensitive instruments which can be photographed at any instant so that the readings can be accurately read later from the photographs. Many variations and combinations of these basic techniques are used along with highly specialized methods.

The simplest method of measurement, however, is to read the standard instruments on the instrument panel and manually record the readings. While there is a potential source of human error involved in reading the instruments, this technique proves surprisingly accurate. It is the primary method used for the experiments described in the following chapters of this text. In some tests, certain items of additional equipment are required to supplement the existing instrumentation. But for most data the standard aircraft instruments are relied upon.

The following information needs to be measured for most tests, using the instruments indicated:

1. Pressure (altitude) — altimeter
2. Temperature — outside air temperature gauge
3. Airspeed — airspeed indicator
4. Engine power — tachometer and manifold pressure gauge
5. Elapsed time — recording feature of tachometer

As discussed above, the altimeter is actually a pressure gauge, and with a pressure setting of 29.92 in Hg it reads pressure altitude regardless of the actual pressure in the atmosphere. Readings are taken in feet of altitude and are converted to an actual pressure value or pressure ratio value in the data reduction.

Temperature is read on a thermometer, which in an aircraft is called the outside air temperature gauge, or OAT for short. Most OAT gauges are calibrated in both centigrade and Fahrenheit. It is more convenient to read temperature in degrees Fahrenheit.

A typical airspeed indicator is shown in Figure 1–4a. Airspeed values are read just as on an automobile speedometer. The meaning of the airspeed value, however, is quite different from the speed reading of an automobile speedometer, as we shall see in a later experiment. Airspeed is calibrated in either knots or miles per hour, or sometimes both scales appear.

For some experiments, it is necessary to know the power that the engine is developing. This can be calculated from the rotational speed of the propeller and the pressure in the intake manifold. The tachometer measures propeller RPM and is calibrated in hundreds of RPM. Figure 1–4b shows a typical tachometer indicating 1700 RPM. The manifold pressure is indicated in inches of mercury on the manifold pressure gauge (Figure 1–4c).

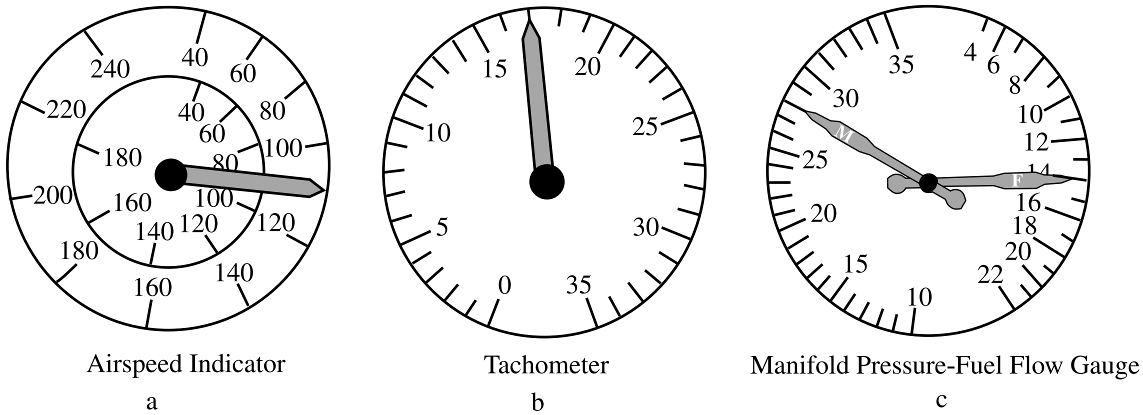

Figure 1–4 Aircraft instruments. (a) Airspeed indicator; (b) tachometer; (c) manifold pressure-fuel flow gauge.

Aircraft weight is required for most tests. Because weight is continually changing in flight due to fuel consumption, it is necessary to determine the weight at the exact time of the particular test. The simplest way to do this is to completely fill the fuel tanks before take-off and record the weight at that time. The time is recorded by the elapsed time feature of the tachometer or a stopwatch. This part of the tachometer (see Figure 1–4b) is similar to the odometer feature of an automobile speedometer except that it records hours of engine running time rather than miles traveled. The initial reading is taken at the time the fuel tanks are full. This is called the 'initial tach time'. The tach time is then recorded at the time of each test. The difference between this value and the initial value of tach time multiplied by the hourly fuel consumption in pounds then gives the change in weight from the initial weight. A fuel computer can also be used.

In addition to the standard aircraft instruments, a stop watch is required for many of the tests. This is used to measure the duration of a particular test run.